EUROPA'S ICE SHELL THICKNESS DERIVED FROM THERMAL-ORBITAL EVOLUTION MODELS.

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Introduction

Images of Europa obtained by the *Galileo* spacecraft show a variety of surface features that are generally believed to be related to the thermal state and thickness of Europa's H_2O-layer. A substantial part of this layer is expected to be liquid, forming a subsurface ocean of up to about 100 km thickness. This is suggested by the detection of an induced magnetic field at shallow depth [1], by equilibrium models of the heat production and heat transport rates through the ice shell (e.g.,[2, 3]), and by the interpretation of geological surface features (e.g.,[4]). The latter show evidence for both a thick ice shell of a few tens of kilometers and a thin ice shell with a thickness of only a few km, or even just a few hundreds of meters. The absolute ages of these surface features are unknown. Therefore, we calculated thermal orbital evolution models in order to determine Europa's ice thickness as a function of time. Different phases of ice thickness may be related to different kinds of surface features. Another important question addressed in this study is the following: Can the ocean exist for several Ga?

Since the inner three Galilean satellites are locked in the Laplace resonance, the history of Europa cannot be understood without considering the evolutions of its neighbouring satellites Io and Ganymede. Due to the resonance, the orbital periods of Io, Europa, and Ganymede are close to the ratio of 1:2:4 and their forced eccentricities are maintained over long periods of time. A part of the orbital energy gained by Io due to tidal interaction with Jupiter is dissipated as heat in Io's and Europa's interior (e.g.,[5]). Ganymede's dissipation rate is negligible during the evolution in the Laplace resonance. It may have been important though during formation of the resonance. The gravitational interactions between Io and Jupiter tend to drive the satellites deeper into resonance and to increase their mean motions. Dissipation in the satellites tends to drive them out of resonance and thereby to decrease their eccentricities and mean motions. Due to these opposing effects oscillations are possible, where the orbital elements and the dissipation rates vary considerably [6, 7]. These variations of Europa's (and Io's) thermal state may serve as an explanation for different kinds of surface features on Europa.

The Model

Basically, our model consists of four parts:

1. *Interior structure*: We assume that Io and Europa are differentiated into an iron-rich core and a silicate shell. Additionally, there is the H_2O-layer on Europa. These models are consistent with the moments of inertia of the satellites derived from *Galileo* data [8, 9].

2. *Tidal heating*: The rheology of the viscoelastic layers is cast in terms of a Maxwell model with temperature dependent viscosity and rigidity. In case of Io tidal dissipation occurs in the silicate shell. For Europa we consider two different models. In model 1 dissipation is restricted to the silicate layer. In model 2 dissipation within the ice layer is assumed. The tidal forces are determined by the potential Love number k_2, which is a function of rheology and thus temperature. The dissipation rate Q_{diss} is then given by [10]

$$Q_{diss} = -\frac{21}{2}\frac{R^5 n^5 e^2}{G}\mathrm{Im}(k_2), \qquad (1)$$

where R is the satellite's radius, n the mean motion, e the eccentricity, and G the gravitational constant.

3. *Heat transfer*: To calculate the heat transfer rate through the silicate shells and Europa's ice layer a parameterized model of convection is used. The time dependence of the thickness of the conductive stagnant lid is determined from energy balance equations. As heat sources we take into account the tidal dissipation rates and radiogenic heating from the rocky layers.

4. *Orbital evolution*: The satellites evolve in the Laplace resonance. Ganymed is included as a point mass in the orbital equations, which are based on the models described in [5] and [7]. Dissipation in Jupiter is parameterized by the dissipation coefficient Q_J. This value and the initial mean motions are chosen such that the present-day orbital configuration of Io, Europa, and Ganymede is reproduced at 4.6 Ga.

The link between all four parts of the model is provided by the dissipation rate depending on the orbital elements as well as on structure, rheology and temperature (Eq.1).

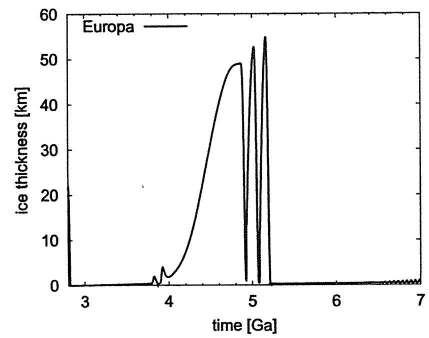

Figure 1: Equilibrium ice thickness according to heat production of model 1 (dissipation within Europa's silicate shell).

Results

The orbital evolution of Io and Europa can be devided into different phases, which are closely related to the ice thickness due to the different dissipation rates and corresponding heat productions. The phases, which are discussed in detail in [11], include equilibrium phases as well as oscillatory phases. Here we focus on the implications for Europa's ice shell thickness. Examples are shown in Figs.1–3. The current state, is obtained at 4.6 Ga in all models. In Fig.1 the result is shown for model

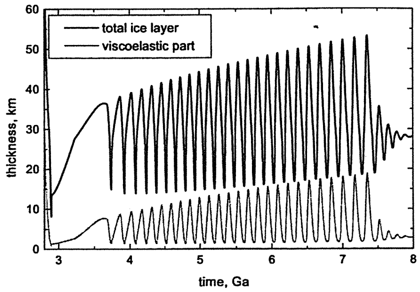

Figure 2: Ice thickness according to model 2 (dissipation within Europa's ice layer).

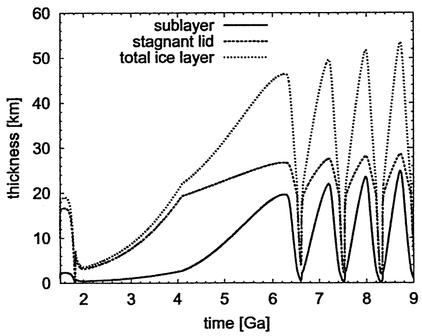

Figure 3: Ice thickness according to model 2 including lithospheric evolution in Io.

1, where dissipation in Europa is restricted to the silicate shell. The thickness of the ice layer is estimated from the heat flow out of the silicate shell using equilibrium conditions for the ice shell. The present-day thickness of the ice shell is about 30 km. Europa is in this case in a phase of increasing ice thickness. The eccentricity is decreasing, while the mean motion is increasing implying that the satellites move away from Jupiter (not shown here). However, there are thin-ice phases with thicknesses smaller than 1 km about 600 Ma b.p. Oscillations are initiated at about 4.8 Ga. After the oscillations there is another phase where Europa is in a high temperature state accompanied by small ice thicknesses.

In Figs.2 and 3 the evolution is shown for model 2, where dissipation in Europa is restricted to the ice layer. In Fig.2 the total thickness of the ice layer and the thickness of its viscoelastic part are shown. The difference between these values equals the thickness of the upper conductive lid. The current state is obtained during the oscillatory phase. Again, the thickness is about 30 km. However, there are variations in total ice thickness in the range of about 10–40 km on a period of about 200 Ma. In this case there are no phases with ice thicknesses smaller than 10 km.

In Fig.3 the thermal model of Io is changed. In Fig.2 it is assumed that convection within Io occurs in the whole mantle and that it is driven by the temperature difference between interior mantle temperature and surface temperature. In Fig.3, a conductive lithosphere is included in the Io-model. In this case the satellites evolve more slowly. The present state is obtained before oscillations are initiated. The current thickness of Io's lithosphere is about 12 km (not shown here). Using this Io-model it is not possible to satisfy Io's heat flux constraint of at least 2 Wm^{-2} [12, 13]. The value derived from these models is 0.1 Wm^{-2}. This suggests that other heat transfer mechanisms instead of thermal conduction through the lithosphere are more important for the present Io.

In all the models the thickness of Europa's ice layer is less than about 60 km. Since the total thickness of the H_2O-layer exceeds 70 km with most likely values of more than 100 km, our results suggest, that the ocean is present over geological timescales. Different surface features on Europa may be related to different phases of ice thickness. This implies that the chaos terrain, which is generally believed to be one of the youngest features on Europa was formed more than 100 Ma b.p. However, according to our derived present-day ice thickness of 30 km, domes formed by upwelling plumes in the convecting ice are better candidates for the most recent features. Note, that the present-day value of ice thickness is independent of the chosen model.

The formation of features in a thin ice layer of only a few km or less, requires substantial tidal heating within the silicate shell. This additionally requires relatively high eccentricities, which will ecceed the currently observed values. This is further evidence for an ice shell thickness of a few tens of km for the present Europa.

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